Supplementary Materials S1 Dynamic Craft Model Overview

S1.1 Description of Dynamic Craft Model (DCM) Phosphorus Component

In the new variant DynamicCRAFT (DCM) the P component of TOPCAT-NP [41] was adopted. We replaced both the OCM's original linear function that represented the entrainment by surface runoff of particulate P as a function of the runoff depth, and the constant CSS(SRP) parameter with the following set of equations which are timestep independent (in this application the timestep used was daily):

$$PTOP(0) = Pinitial\ P_{DIST} \quad \text{(S1a)}$$

Where *PTOP(0)* is the initial value of P in the 1cm upper layer of soil and *Pinitial* the total soil P content (units kg P ha^{-1}). The remaining soil P is bound in the lower soil layer, i.e. root zone and has an initial value of *PSOIL(0).*

Therefore $PSOIL(0) = Pinitial - PTOP(0)$ (S1b)

Soluble reactive P (SRP) flux (*LSRP(SS)*) in the fast subsurface flow (runoff) pathway is calculated from the available reserve of soil P (*PSOIL(t)*) at each timestep using Equation (S2a), where f(L) is the fraction of P leached in the timestep and K_D the adsorption/desorption coefficient (usually fixed at 0.15 based on sensitivity simulations). The factor of 10 is included to enable the calculated flux to have the correct units.

$$LSRP(SS)(t) = 10\ PSOIL(t)\ f(L)\ K_D \quad \text{(S2a)}$$

and finally concentration (*CSRP(SS)*) is given by Equation (S2b) where $q_{SS}(t)$ is the fast subsurface flow (in m per timestep)

$$CSRP(SS)(t) = LSRP(SS)(t) / q_{SS}(t) \quad \text{(S2b)}$$

The leaching function $f(L)$ was adapted from the TOPCAT-NP model and combines a cubic with a constant value depending on the value of a variable ε, which is given by the following (Equation (S3)) as a function of the water holding capacity of the soil ϕ (in mm) and the cumulative fast subsurface flow ($\sum q_{SS}$ - which was used in place of Hydrologically Effective Rainfall (HER) simulated by TOPCAT-NP) , the units of the two terms have to be identical

$$\varepsilon = \sum q_{SS} / \phi \quad \text{(S3a)}$$

$f(L)$ is then a function of ε based on the TOPCAT-NP's nitrate leaching model [41]

$$f(L) = 1.111\ \varepsilon - 0.203\ \varepsilon^3 \quad \text{for} \quad \varepsilon \leq 1.34 \quad \text{(S3b)}$$

$f(L) = 0$ for $\varepsilon > 1.34$ (S3c)

The fraction of P in the store leached ($f(L)$) is therefore time-varying as $\sum q_{SS}$ increases over time during the year, as more soil water is leached into the fast subsurface store, with $\sum q_{SS}$ resetting to zero when the soil P is replenished at a user-specified annual date. The soil P store is thus depleted at each timestep by the following balance equation (S4):

$PSOIL(t) = PSOIL(t-1) - LSRP(SS)(t)$ (S4)

Particulate P (sediment) sub-model

The loss of sediment-attached (or "particulate") P uses algorithms originating from the work of Sharpley and Menzel in the early 1980s [42] The concept of an *enrichment ratio (ER)* was used where the eroded soil was found to be richer in P than the source soil. The *ER* is calculated dynamically in the sub-model as a function of the suspended sediment concentration (*SED(t)*). In DynamicCRAFT the surface runoff (q_{SR}) and *SED(t)* are supplied from the water flow and sediment transport components of the model at each time-step.

Firstly, the sediment yield (*SY*) at each timestep is calculated by Equation (S5) from the variables introduced above

$SY(t) = q_{SR}(t)\, SED(t)$ / 100 (S5)

Then, the *ER* is calculated by Equation (S6)), from [42]

$ln(ER(t)) = 2 - 0.2\, ln(SY(t))$ (S6)

Next, the loads of PP and TRP transported by surface runoff (*LPP(SR)(t)*, *LTRP(SR)(t)*) are calculated by Eq. S7

$LPP(SR)(t) = (PTOP(t)\ \ ER(t)\ SY(t)) / SBD$ (S7a)

$LTRP(SR)(t) = LPP(SR)(t)\ K_{PART}$ (S7b)

Where *SBD* is the sediment bulk density (M L^{-3}). In order to calculate the TRP load and concentration in the surface runoff flow pathway using Equation (S7a) partitioning coefficient K_{PART} from the OCM is employed. In the TOPCAT-NP model its value was set to 1/175 which led to extremely small TRP concentrations and loads in surface runoff.

PTOP is updated at each timestep, i.e. the P store is depleted after runoff events and replenished on a user-specified date, which in these DCM simulations takes place annually on the same day. *PTOP is* given by Equation (S8)

$$PTOP(t) = PTOP(t-1) - LPP(SR)(t)\ (1+K_{PART}) \quad \text{(S8)}$$

Lastly, the P loads calculated by CRAFT in each flow pathway are modified to use the new loads *LPP(SR), LTRP(SR)* and *LSRP(SS)* from the DCM in place of the loads calculated using fixed concentrations. The "Outlet" mixing model (Figure 2 in main paper) combines the different P fluxes in the surface and fast subsurface flow pathways with the P flux from the (unchanged from the OCM) slow groundwater flow pathway. Following this the TP and TRP concentrations in the catchment runoff (total runoff from all three flow pathways added together) are calculated from the total fluxes in each flow pathway, in the usual manner.

S 1.2 Parameter Sets Derived from Model Calibration

Refer to [39] for definitions of each parameter in the DCM variant of the CRAFT and the main paper's Methods for the OCM variant's parameter definitions. Parameter Set numbers in Table S1 below refer to the MultiCRAFT simulations described in the Methods. Set 4 was a "High WQ" set derived from Set 2 for sub-catchments that achieved "Good" or better WFD status and did not require any LRs.

Table S1 Model Parameters Calibrated in OCM and DCM MultiCRAFT Simulations

Parameter Name & (Units)	Set 1	Set 2	Set 3	Set 4
S_{DMAX} (mm d^{-1})	7.5	6.0	10.0	6.0
S_{RMAX} (mm)	67	21	54	21
K_{SURF} (d^{-1})	0.38	0.38	0.38	0.38
K_{SPLIT} (–)	0.59	0.59	0.3	0.59
K_{GW} (d^{-1})	0.035	0.035	0.08	0.035
K_{SS} (d^{-1})	0.31	0.37	0.37	0.37
$K_{SR}(PP)$[1] (mg P L^{-1} mm^{-1})	0.02	0.02	0.12	0.02
$C_{SS}(SRP)$[1] (mg P L^{-1})	0.17	0.14	0.36	0.05
$C_{GW}(SRP)$ (mg P L^{-1})	0.02	0.015	0.03	0.01
P_{DIST}[2] (–)	0.95	0.95	0.95	0.95
$P_{INITIAL}$[2] (kg P ha^{-1})	1.2	1.0	2.3	0.4

[1]These parameters are only used in the OCM variant of the CRAFT
[2]These parameters are only used in the DCM variant of the CRAFT